Adiabatic frequency conversion of quantum optical information in atomic vapor

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We experimentally demonstrate a quantum communication protocol that enables frequency conversion and routing of quantum optical information in an adiabatic and thus robust way. The protocol is based on electromagnetically-induced transparency in systems with multiple excited levels: transfer and/or distribution of optical states between different signal modes is implemented by adiabatically changing the control fields. The proof-of-principle experiment is performed using the hyperfine levels of the rubidium D1 line.

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Introduction An essential element of a quantum optical communication network is a tool for transferring and/or distributing quantum information between optical modes (possibly of different frequencies) in a loss- and decoherence-free fashion. This is important not only for routing quantum information, but also for interfacing quantum communication lines of different wavelength (e.g. fiber-optical and open-air) between each other and with memory-based quantum repeaters [1, 2, 3].

Some experiments on frequency conversion of quantum states of light have been performed using nonlinear optical effects in crystals [4, 5] and periodically-poled waveguides [6]. Conservation of quantum information in such a transformation has been demonstrated in Ref. [7]. Refs. [8, 9] reported an alternative approach, involving storage of light by means of electromagnetically induced transparency (EIT) [10] and its subsequent retrieval on another optical transition.

In this paper, following our group's recent proposal [11], we experimentally demonstrate a protocol for routing and frequency conversion of optical quantum information via EIT in an atomic system with multiple excited levels. Our method is related to that of Refs. [8, 9], but here the information is transferred *during the propagation*, thus avoiding the losses associated with the storage of light. By means of the EIT control fields we control the composition of the optical component of the dark-state polariton, and can convert, completely or partially, the incoming signal state into another optical mode.

Our scheme (that we call RATOS, Raman adiabatic transfer of optical states) resembles stimulated Raman adiabatic passage (STIRAP) [12], but applies to optical rather than atomic states. Thanks to its adiabatic character, the efficiency of RATOS does not strongly depend on the parameters of the control fields, but only on their initial and final values, which is favorable for possible practical applications of the method.

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Theory We consider a double-Λ system as shown in Fig. 1(a), with the rubidium D1 transition as a model. The energy levels are coupled by two weak signal fields, described by their annihilation operators $\hat{a}_1$ and $\hat{a}_2$, and two strong control fields, described by their Rabi frequencies Ω_1 and Ω_2. As shown in Ref. [11], and later, independently, in Ref. [13], such a system exhibits EIT for a single optical mode, a superposition

$$\hat{b} \propto \left[\frac{\Omega_1}{g_1}\hat{a}_1 + \frac{\Omega_2}{g_2}\hat{a}_2\right], \tag{1}$$

of the signal fields, with g_i being the vacuum Rabi frequency for the ith signal mode.

The experiment proceeds as follows. With only control field 1 (hereafter called pump) initially present, a pulsed optical state in mode $\hat{a}_1$ (signal) is coupled into the medium. While it is propagating, control field 2 (retrieve) is turned on slowly, so the EIT signal mode is adiabatically converted into a superposition (1), which continues to propagate losslessly through the cell [11].

If the pump field is left on, the optical state that has entered the cell in mode $\hat{a}_1$ will leave it in mode $\hat{b}$. This allows the implementation of beam splitting for optical modes of different frequency, with the final intensities of the two control pulses determining the outcome of the process. The beam splitting ratio is given by

$$\frac{\langle\hat{a}_2\rangle}{\langle\hat{a}_1\rangle} = \frac{g_1\Omega_2}{g_2\Omega_1}. \tag{2}$$

The power $P_{\hat{a}_2}$ in the created field mode $\hat{a}_2$ can be expressed using the power P_i of the two control fields and the incoming signal field via

$$P_{\hat{a}_2} = \frac{P_2}{cP_1 + P_2} P_{\text{signal}}, \tag{3}$$

where c is a constant depending on the oscillator strengths μ_{ij} of the transitions used and the beam radii r_i of the two control fields Ω_i,

$$c = \frac{\mu_{24}^2\mu_{13}^2}{\mu_{14}^2\mu_{23}^2}\frac{r_2^2}{r_1^2}. \tag{4}$$

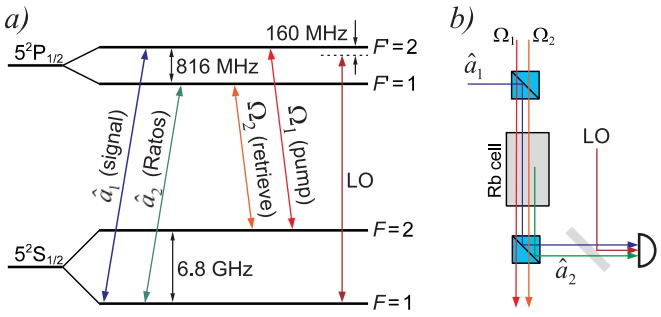

FIG. 1: a) The transitions used in the experiment, as described in the text. Also shown is the local oscillator field (LO) used for heterodyne detection. b) A sketch of the experimental setup. In the actual experiment, the beams are overlapping in the cell, the separation in the drawing is for clarity.

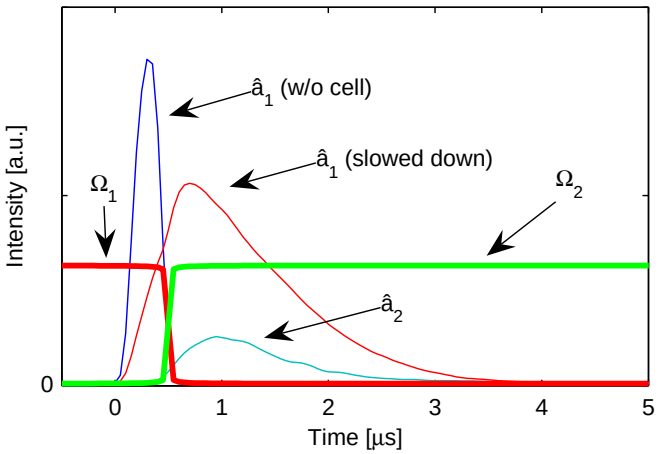

FIG. 2: Temporal profiles of the fields. The two control pulses Ω_1 and Ω_2 are switched, respectively, off and on on when the signal pulse enters the cell completely, giving rise to a Ratos pulse ($\hat{a}_2$). Also displayed is the signal pulse $\hat{a}_1$ in the absence of the cell (scaled down) and the slowed down signal pulse in the presence of a constant pump field (regular EIT).

If the pump field is instead adiabatically switched off while mode $\hat{b}$ is propagating through the cell, the initial quantum state of mode $\hat{a}_1$ will be fully transferred to mode $\hat{a}_2$, thus completing the RATOS protocol.

Experimental Setup The experiment is performed in warm rubidium-87 vapor at 60°C in a 5-cm long cell filled with 5 Torr of neon as a buffer gas. The cell is mounted within a magnetically shielded oven. The double-Λ system is realized using the hyperfine levels of the 795-nm D1 line, with the $5S_{1/2}$ hyperfine levels as the two ground states, which are coupled via three laser fields to the $5P_{1/2}$ manifold [Fig. 1(a)].

The optical setup is shown in Fig. 1(b). The signal field was provided by a Coherent MBR-110 Ti:Saphire laser with a narrow spectral width (∼40 kHz) and high long-term stability. The beam was frequency shifted by 160 MHz using an acousto-optical modulator (AOM) in a double-pass configuration, which allowed switching of the signal field. The pump and retrieve fields were obtained from external-cavity diode lasers sequentially phase-locked to each other and the Ti:Sapphire laser. Both phase lock circuits were programmed to ensure that the frequency difference among the three fields entering the cell corresponded to the hyperfine splitting frequencies of the ground and excited levels of the rubidium D1 transition: 6835 and 817 MHz, respectively. The bandwidth of the beat signal in each phase lock circuit did not exceed 10 Hz. Each of the diode laser beams was controlled by an AOM driven at 80 MHz.

Before entering the rubidium cell, the beams were combined with the signal beam on a polarizing beam splitter, so the linear polarization of the control beams is orthogonal to that of the signal and RATOS beams. The spatial modes of the input optical fields were carefully matched to each other.

After passing through the cell the two signal fields were separated from the control beams using a polarizing beamsplitter, and subjected to heterodyne detection on a fast photodiode. The role of the local oscillator was played by the unmodulated field of the Ti:Sapphire laser. The beat signal at 160 MHz (signal beam) or 657 MHz (Ratos field) was measured using a spectrum analyzer in the zero span mode, with a temporal resolution of 200 ns.

We performed a set of preliminary measurements to verify the functionality of our setup. First, with all three input fields continuously on, we observed generation of a continuous field on the $|5S_{1/2}, F = 1\rangle \leftrightarrow |5P_{1/2}, F = 1\rangle$ transition due to four-wave mixing. Second, we checked that the signal field experienced EIT when only the pump field was present and observed slowdown of the 400-ns signal pulse. Third, we performed a "classic" storage of light experiment [2] by turning the pump field off after the signal pulse entered the cell, and turning it back on after a few hundred μs. Fourth, we stored the signal pulse and then recovered it on the Ratos transition using the retrieve field akin to the experiment by Zibrov and co-workers [8]. Finally, by reducing the delay between the turn-off of the pump and the turn-on of the retrieve field to small negative values, we observed RATOS.

Figure 2 shows typical pulse forms for the two control fields, the incoming signal field, and the Ratos pulse. Also shown is the slowed down signal field, observed in normal EIT conditions (constant pump field, no retrieve field). As evident from the figure, RATOS is indeed capable of transferring light from mode $\hat{a}_1$ into $\hat{a}_2$, with a efficiency of approximately 20% with respect to the slowed down pulse for this particular measurement. However, as will be shown later, this benchmark could be increased to over 70%.

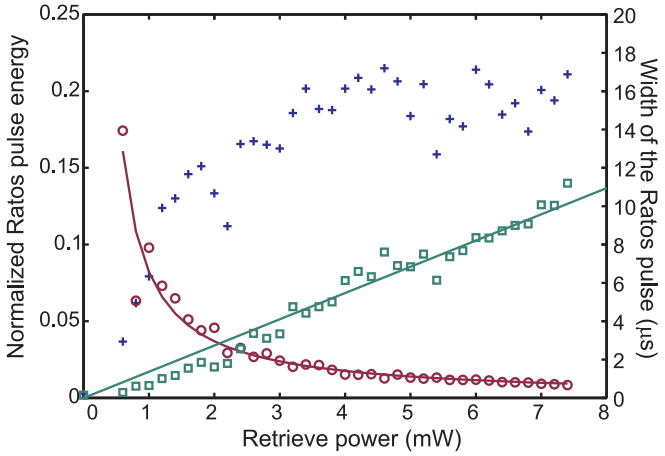

FIG. 3: Peak power of the retrieved Ratos pulse (□), its temporal width (○), and energy (+) as a function of the power of the retrieve laser. The energy is normalized to the energy of the slowed down pulse. The peak intensity plot is in arbitrary units. The solid lines are a linear and inverse linear fits.

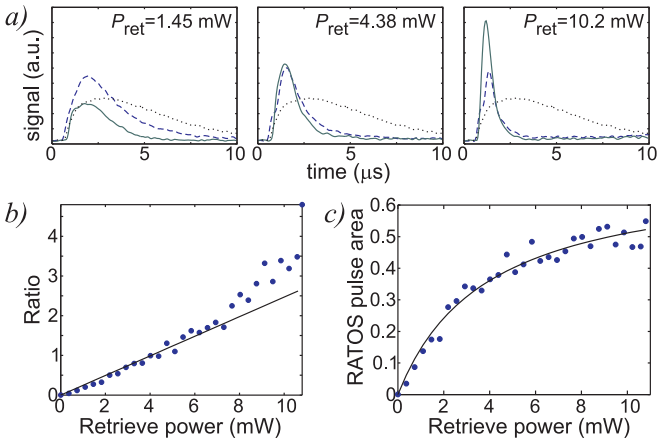

FIG. 4: Beam splitting via RATOS. a) Example waveforms for different retrieve pulse powers $P_{\rm ret}$; the pump power remains constant at 4 mW. The Ratos field ($\hat{a}_2$) is shown with a solid line, the transmitted signal field ($\hat{a}_1$) with a dashed line. The dotted line displays the transmitted, slowed down signal pulse in the absence of the retrieve field (regular EIT). (b) Energy ratio of the Ratos pulse and the transmitted signal pulse, as a function of the retrieve field power. (c) Energy of the restored Ratos pulse normalized to the energy of the slowed down pulse; the solid line is a least square fit of Eq. (3) giving a highest efficiency of 70%.

Adiabaticity In classical four-wave mixing, the electric field of the created mode is proportional to the electric field of the three mixing fields: $\langle\hat{a}_2\rangle \propto \Omega_1\Omega_2\langle\hat{a}_1\rangle$. In contrast, the adiabatic transfer process studied here should not depend on the exact parameters of the control fields, as long as the switching takes place while the signal pulse is inside the cell. We verified the adiabatic nature of our experiment by varying the intensity of the retrieve field and monitoring the shape of the output RATOS pulse.

The result of this measurement is shown in Fig. 3. As expected, the time integrated intensity of the Ratos pulse shows only a weak dependence of the created field mode for sufficiently high retrieve field intensities. With the retrieve field below 2 mW, the EIT effect was not sufficiently pronounced so the Ratos pulse experienced partial absorption. The residual dependence for higher powers is due to a Gaussian geometric profile of the control fields, so the EIT was poor in the wings of the beams.

The Ratos pulse *shape*, on the other hand, depends strongly on the control field parameters. As evidenced by Fig. 3, the peak intensity and the temporal width of the Ratos pulse are, respectively, proportional and inversely proportional to the power of the retrieve laser Ω_2. This is because the group velocity of the signal pulse in an EIT medium is proportional to the width of the EIT resonance [10]. The latter, in a Doppler-broadened, weakly decohering medium is essentially proportional to the control field intensity [14].

Optical Beam Splitting In order to realize an optically controlled beam splitter, the pump field Ω_1 was kept on continuously, while Ω_2 was turned on when the signal pulse had fully entered the Rubidium cell. In this case the quantum state of the signal mode $\hat{a}_1$ was transferred into a superposition $\hat{b}$ of the modes $\hat{a}_i$, given by Eq. (1). In the experiment the power of the pump field was kept constant at 4 mW, and the signal fields $\hat{a}_1$ and $\hat{a}_2$ were measured for different powers of the retrieve field.

The results of the optical beam splitting experiment are shown in Fig. 4. The three waveforms of the output signal and Ratos fields at different retrieve field powers [Fig. 4(a)] illustrate the dynamics of multimode dark-state polaritons in the EIT medium. Even though the pump field remains the same in all three plots, the group velocity of the signal pulse (which couples to the pump field through an excited level) increases with the intensity of the retrieve field. This happens because in the presence of the retrieve field, the signal is no longer an independent EIT mode, but a part of a multimode dark-state polariton whose group velocity is proportional to the weighted quadratic mean of all the control Rabi frequencies [11].

The waveforms in Fig. 4(a) also show that the energy ratio of the Ratos and output signal fields increases with the retrieve intensity. This is to be expected according to Eqs. (1) and (2): the fraction of a particular signal field in a multimode polariton is proportional to the Rabi frequency of the associated control field. This proportionality is further illustrated in Fig. 4(b). The observed deviation from the linear fit is due to a systematic error in evaluating the output signal energy: at high retrieve powers, the signal is small so the relative error becomes significant.

If the energy of the retrieved pulse $\hat{a}_2$ (normalized to the slowed down pulse) is plotted against the power of

the control field Ω_2 a dependence given by Eq. (3) is expected. In Fig. 4(c), this function is fitted to the data, with a coefficient a added as an overall efficiency of the process. The fit yields a transfer efficiency of a=70% with respect to the slowed down pulse.

Conclusions In this letter we have demonstrated the possibility for adiabatic frequency conversion and routing of optical information carried by light between two EIT modes in a multi-Λ energy level configuration. The experiment has been carried out using hyperfine levels, with the two weak fields being nearly degenerate, but it can be easily implemented in other level schemes, e.g. using the signal field resonant to the Rubidium D1 transition, while the D2 line is used to create the Ratos field. The demonstrated technique is particulary useful in solid state systems [15], where the level structure allows access to nearly arbitrary frequencies for the created Ratos pulse.

We foresee that RATOS will find its application in routing and wavelength division multiplexing of quantum optical communication channels as well as for interfacing communication lines of different wavelengths between each other and with quantum memory units. RATOS is also useful in quantum state engineering, as it allows the preparation of a quantum state in a superposition of different optical modes.

The measurements have been performed using classical light pulses, thus the efficient transfer of the quantum state could not yet be demonstrated. To close this gap we are setting up a quantum light source capable of supplying squeezed light or Fock states, which can be used to verify the conservation of the quantum state during the transfer.

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